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Numerical Analysis of Slow-Wave Instabilities in Semicircularly Corrugated Slow-Wave Structure
半円形コルゲートによる遅波構造における遅波不安定性の数値解析

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Dispersion characteristics of semicircularly corrugated structures are analyzed. We examine various semicircular corrugations: single, double and gap semicircular corrugations. The dispersion characteristics and the slow-wave instabilities can be controlled by these corrugations. Since the semicircular corrugations have no corner and can provide a feasible miniaturization technology, those corrugations may be used in order to generate intense electromagnetic waves in higher-frequency region.

1. Introduction

The backward wave oscillator (BWO) is a microwave source driven by the electron beam is injected in the axial direction of a waveguide. The slow-wave structure (SWS) is used to slow the phase velocity of the electromagnetic wave in such devices. Typical SWSs are periodic corrugation of sinusoidal or rectangular formed on the wall of the hollow pipe [1]. The coaxial waveguide has a center conductor on the axis of hollow pipe. A corrugation is formed on either conductor or both conductors [2]. To increase the operation frequency of the BWO, the corrugation is miniaturized. SWSs with rectangular corrugation may be used to obtain terahertz radiations [3,4]. In high-power operation, the corners of rectangle are prone to induce discharge [1]. We consider usage of semicircular corrugations in BWOs, since they have no corner and can provide a feasible miniaturization technology.

2. Numerical Method

In this study, we use the coaxial waveguide assuming an infinitely long and perfect conductor walls. The outer conductor is a straight cylindrical waveguide with constant radius R_{out}. The inner conductor is semicircularly corrugated. Figure 1 shows schematic drawing of single semicircular corrugation in which circular conductors are arranged without any gap on the inner conductor. Here, the R_{in}, h, z_0 are the average inner radius, the corrugation amplitude and the pitch length, respectively. The corrugation wave number is defined as $k_0 = 2\pi/z_0$. Double semicircular corrugation has small semicircle on each groove of semicircularly corrugated structure. Gap semicircular corrugation is an arrangement of semicircles with a gap. In the analysis of the coaxial waveguide with electron beam, a guiding magnetic field B_0 is applied uniformly in the axial direction. An infinitesimally thin annular electron beam with a radius R_b propagates in the axial direction between the outer and inner conductors.

We use the Rayleigh-Bessel method, in which the same functions of electromagnetic fields are assumed inside and outside of the corrugation groove. The gap semicircular corrugation is expressed by a discontinuous function from the inner conductor to the end of the semicircles.

There are two cylindrical waveguide modes: transverse electric (TE) and transverse magnetic (TM) modes. With an electron beam, the transverse beam perturbations in a finite B_0 combine the TM and the TE modes. In this study, the TM (TE) mode is dominant in the EH (HE) mode. The BWO operations are based on TM components. Therefore, TM and EH modes are analyzed in the following.

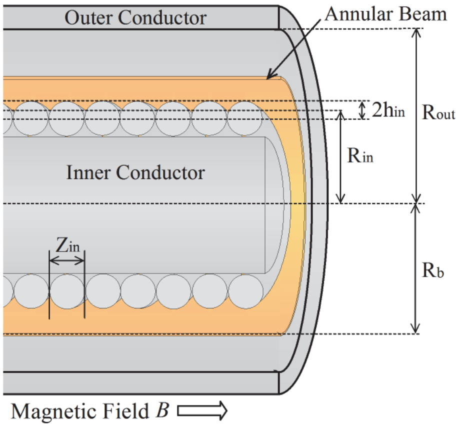

Fig. 1 Schematic drawing of the coaxial semicircular corrugated waveguide.

3. Numerical Results

First, the coaxial waveguide without electron beam is analyzed. Fig. 2 (a) shows the dispersion curves for three kinds of semicircular corrugation. Here, the geometrical parameters are set as R_{out} =1.51 cm, R_{in} = 1.075 cm, z_0 = 0.30 cm and h = 0.075 cm. In Fig. 2 (a), the black, yellow and green lines are the dispersion curves for the single, the double and the gap semicircular corrugation, respectively. One period from 0 to k_0 is shown on the basis of the periodic-zone scheme.

The inner conductor of coaxial waveguide generates the fundamental transverse electromagnetic (TEM) mode. When the inner conductor is corrugated as shown in Fig. 1, the TEM mode becomes a TM dominant surface wave of the inner corrugation and is referred to as the cylindrical surface wave (CSW). The CSW has an upper cutoff frequency at the π point ($k_z z_0 = \pi$). Here, k_z is the axial wave number. The cutoff frequency has the highest value of 43.3 GHz for the single semicircular corrugation. The gap semicircular corrugation has lowest CSW mode with a cutoff frequency of 30.3 GHz. The dispersion curves of the higher-order mode vary by changing semicircular corrugations.

Next, the slow-wave instability of the coaxial waveguide with semicircular corrugations driven by an annular beam is analyzed. In Fig. 2 (b), the temporal growth rates of the gap semicircular corrugation are shown for beam energy of 80 keV, current of 200 A, beam radius R_b = 1.075 cm, and magnetic field B = 0.4 T. The red and blue lines are the growth rates for the Cherenkov and the slow cyclotron instability. As a reference, the corresponding the space charge and slow cyclotron lines are shown in Fig. 2 (a) by dashed and thin lines, respectively. The red and blue lines are the growth rates for the Cherenkov and the slow cyclotron instability. The growth rate of the Cherenkov instability is higher than that of the slow cyclotron instability. Figure 3 shows the peak values of growth rate for fundamental CSW mode and higher-order EH_{01} and EH_{02} modes. The growth rates of the gap semicircular corrugation are higher than those of the other semicircular corrugations. Especially, the Cherenkov growth rate for the CSW mode is twice over other instabilities.

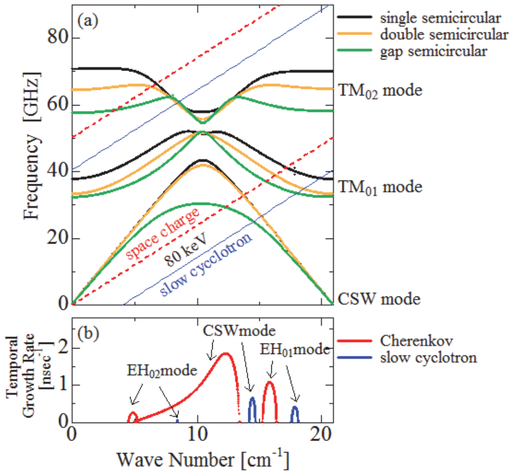

Fig. 2 (a) Dispersion curves each corrugation without electron beam and (b) temporal growth rate for the gap semicircular corrugation.

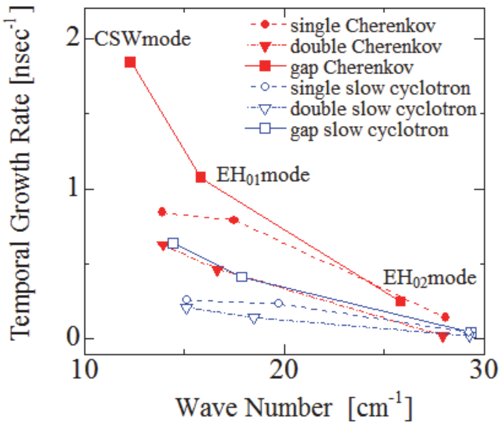

Fig. 3 Peak temporal growth rate versus wave number.

4. Discussion and Summary

We examine numerical accuracy of the Rayleigh-Bessel method by comparing the field matching method, which is free from the Rayleigh assumption. The dispersion curves for rectangular corrugations obtained by the two methods differ by 4.1 % at the cutoff frequency. The numerical errors due to the Rayleigh assumption may be expected to be in same level.

In summary, dispersion characteristics of SWS with semicircular corrugations are examined using single, double and gap semicircular corrugations. The dispersion characteristics and the slow-wave instabilities can be controlled by these corrugations. Semicircular corrugations may be used in order to realize intense radiations with higher-frequency, since those corrugations have no corner and can provide a feasible miniaturization technology.

References

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